EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

3rd Advanced Training Course on Illicit Trafficking and Consequence Management with NUCLEONICA
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Interaction of photons with matter

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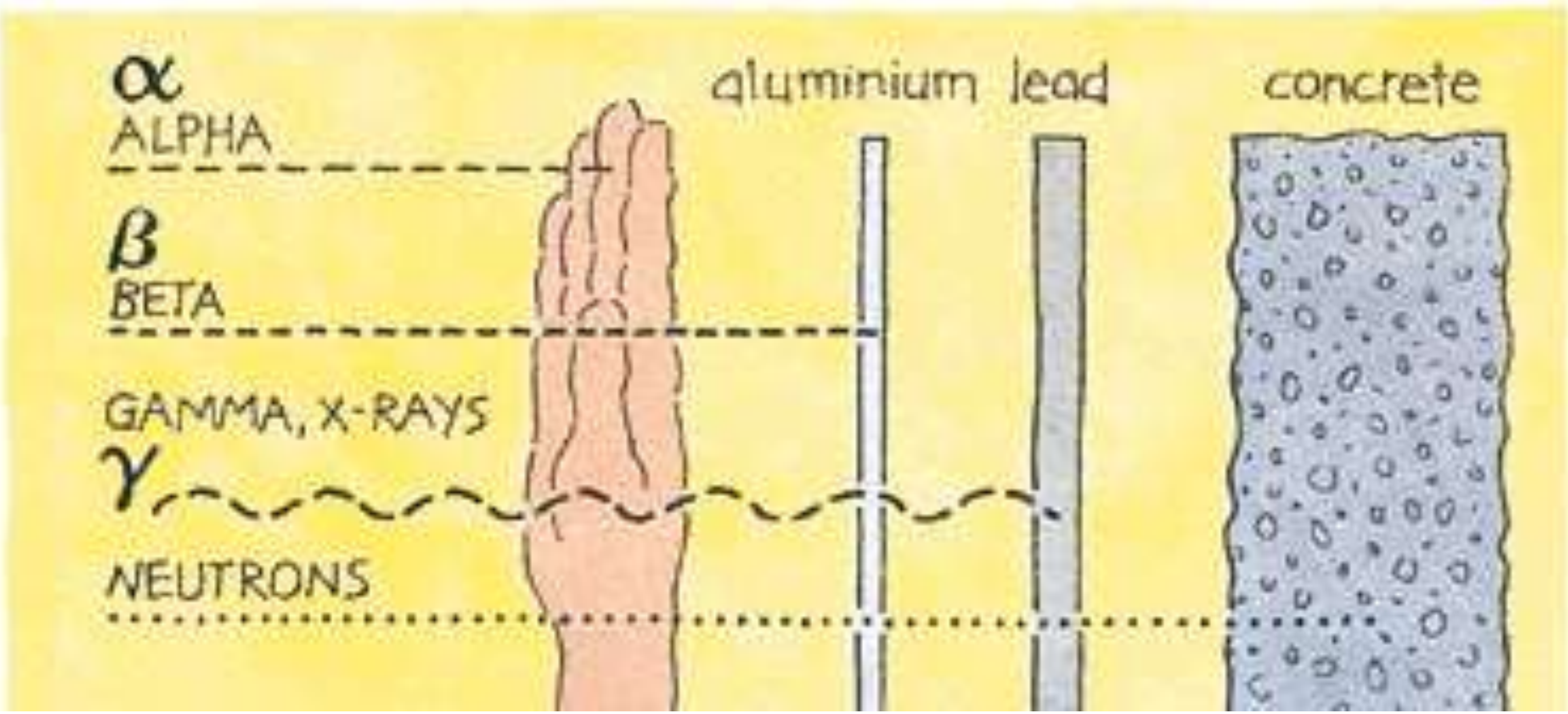
Interaction of photons

Classification of radiations

Type	Radiation	Penetrability
charged particles	• heavy (alpha) • light (beta)	range ~10^{-5} m range ~10^{-3} m
uncharged radiation	• EM (gamma, X) • neutrons	$d_{1/2}$ ~0.1 m $d_{1/2}$ ~0.1 m


α
ALPHA
β
BETA
GAMMA, X-RAYS
γ
NEUTRONS
aluminium
lead
concrete

The photon

✓ Photons are "particle-like" manifestation of electromagnetic waves.

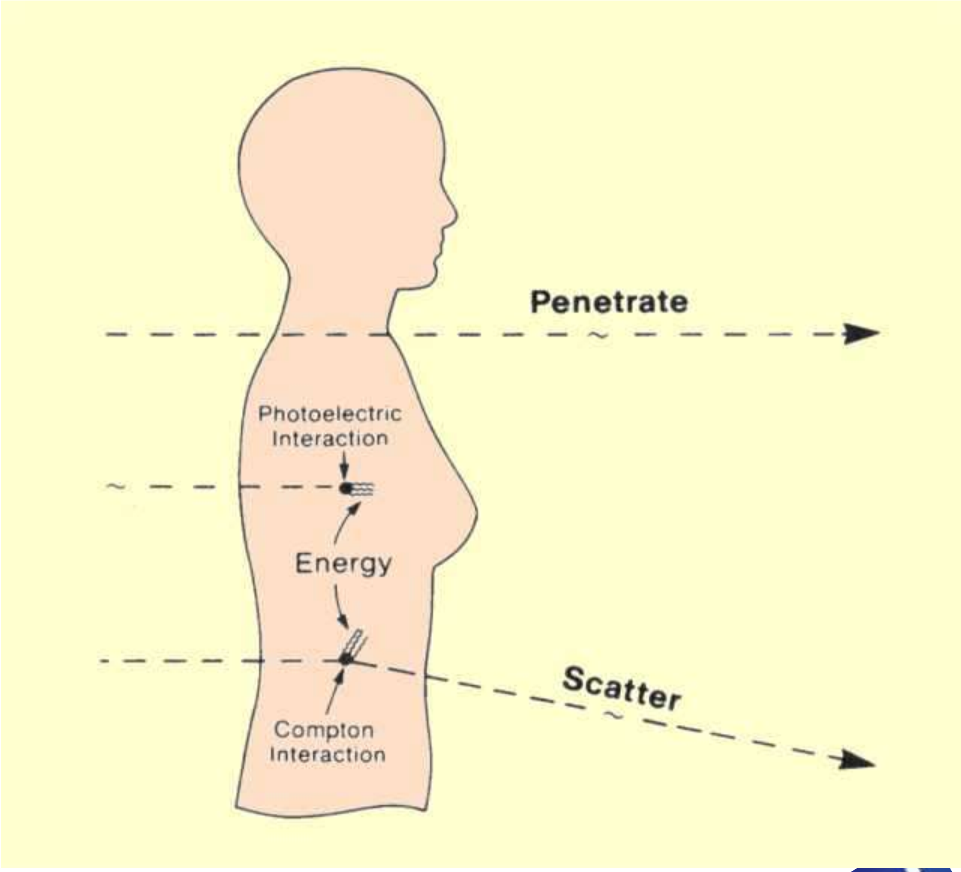
✓ Photon energy is proportional to frequency with a proportionality (Plank's) constant, h = 4.14 x 10^{-21} MeV-sec

$$E = h\nu$$

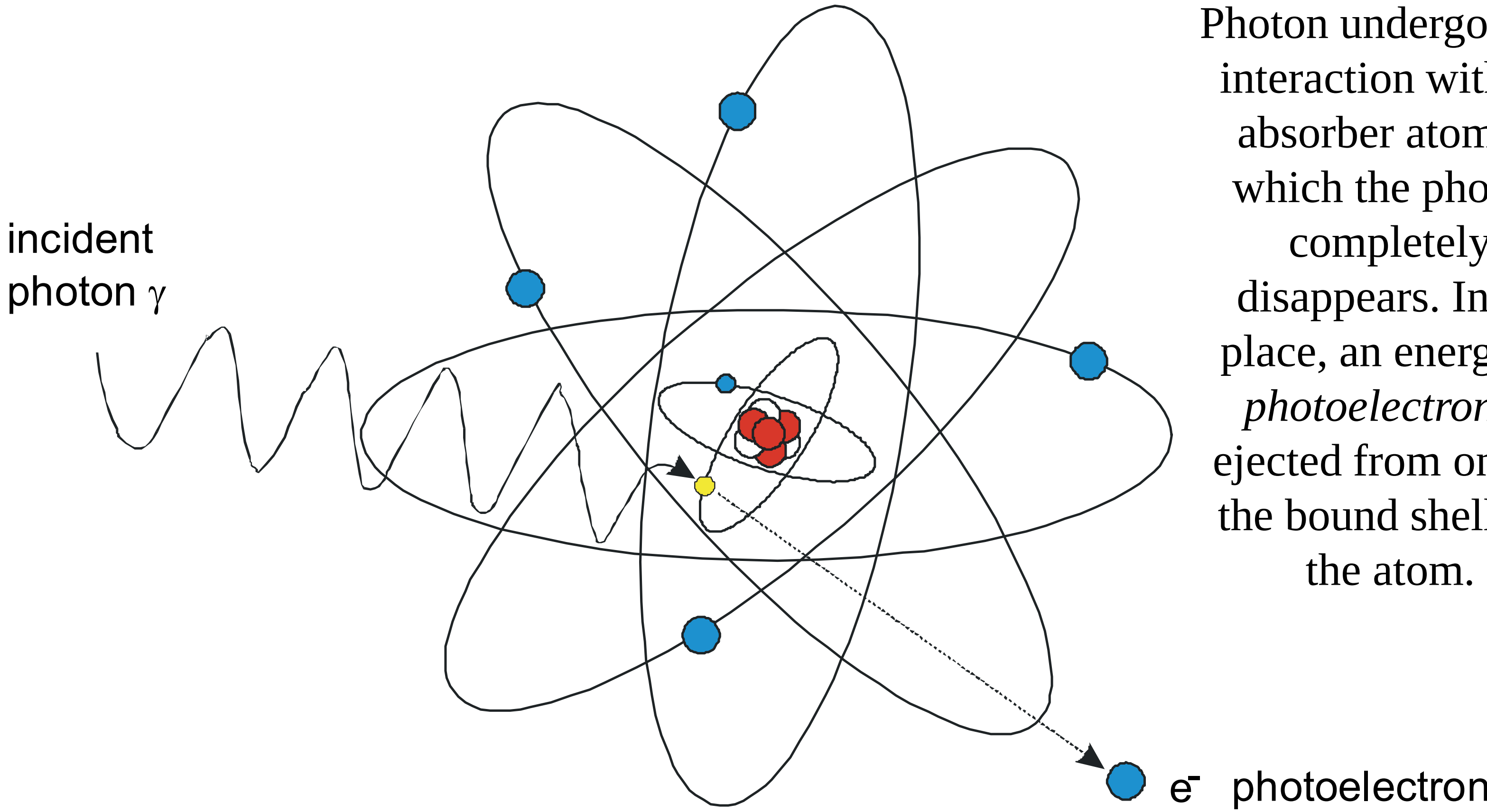
Photons are thus electromagnetic radiation with zero mass, zero charge, and a velocity that is always c, the speed of light. Because they are electrically neutral, they do not steadily lose energy via coulombic interactions with atomic electrons as do charged particles. Instead they travel some considerable distance before undergoing a more "catastrophic" interaction. All of the photon interactions of interest to us in this course lead to partial or total transfer of the photon energy to electron energy. Thus the history of a photon in material is characterized by the sudden disappearance of the photon or by scattering through significant angles with significant energy loss.

Photon interaction with matter

- It can penetrate the section of matter without interacting
- It can interact with the matter and be completely absorbed by depositing its energy
- It can interact and be scattered or deflected from its original direction and deposit part of its energy



Gamma rays: Photoelectric effect

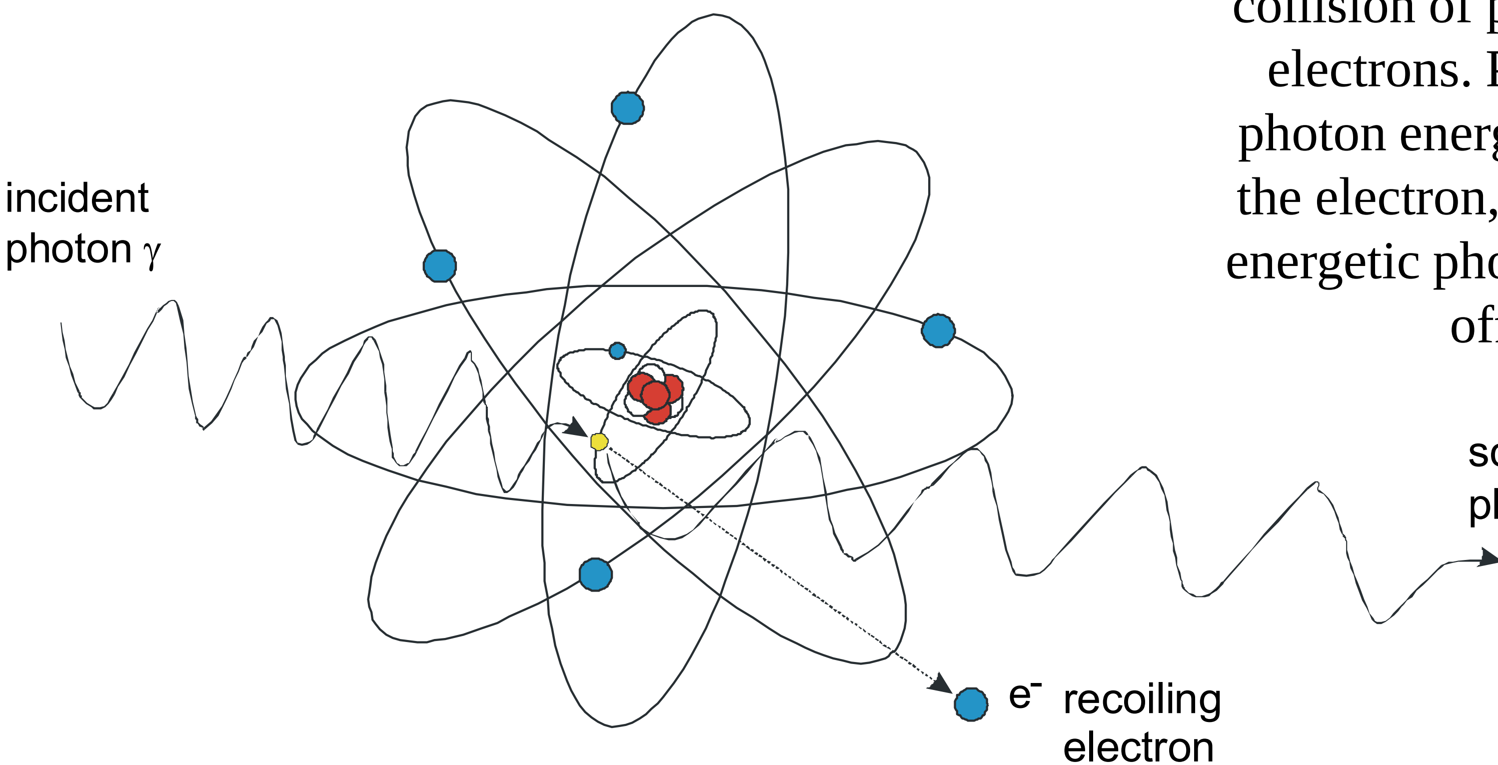


Photon undergoes an interaction with an absorber atom in which the photon completely disappears. In its place, an energetic *photoelectron* is ejected from one of the bound shells of the atom.

$$PE \propto Z^{(4-5)} / E^3$$

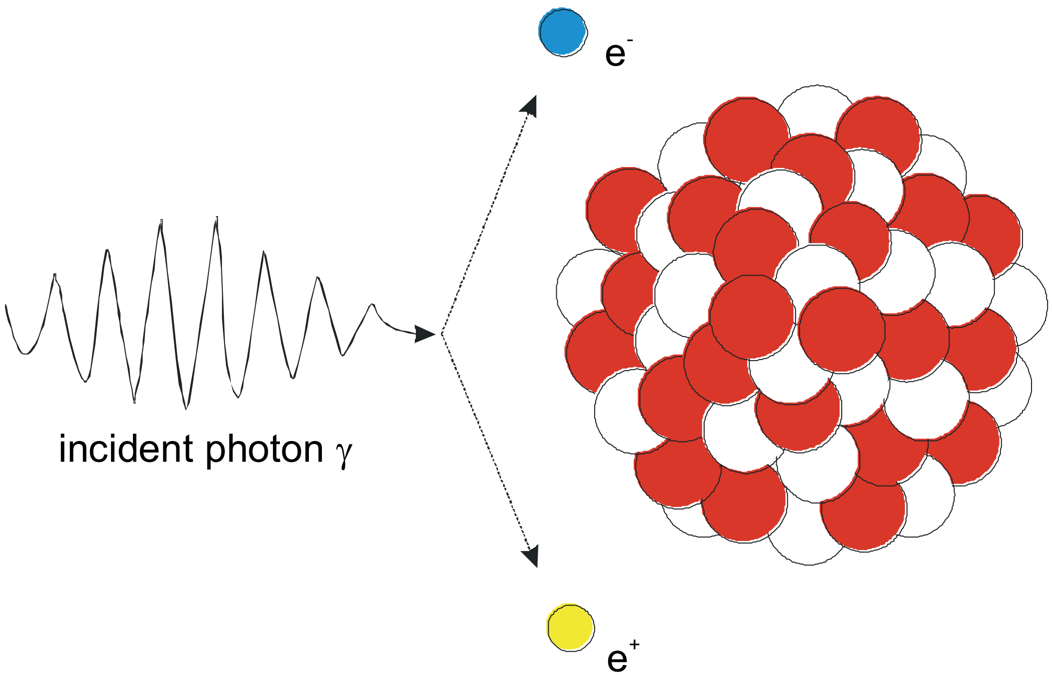
Gamma rays: Compton scattering

The **Compton effect** is equivalent to inelastic collision of photon with electrons. Part of the photon energy is lost to the electron, and a less-energetic photon bounce off.



Note: scattering – not absorption!

Gamma rays: Pair production

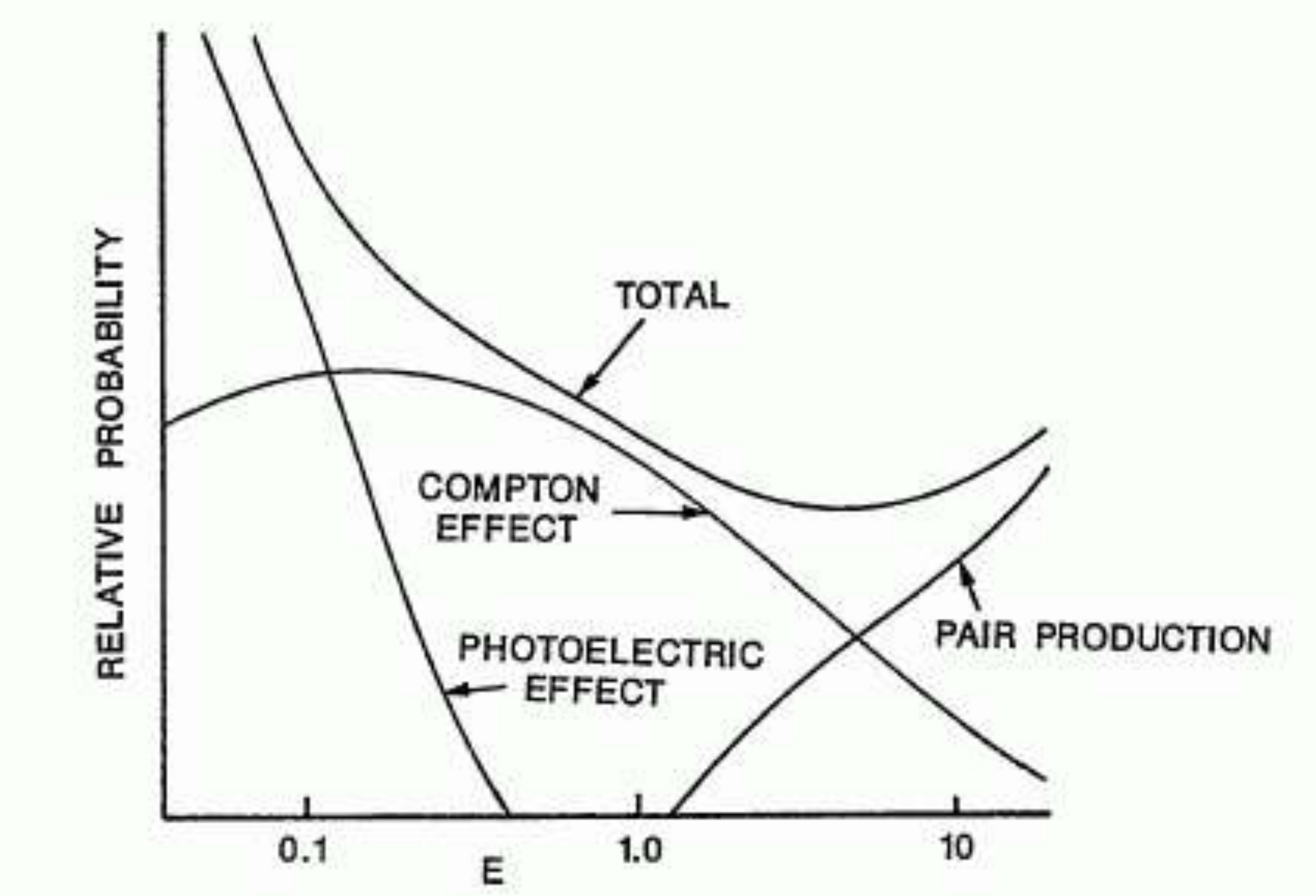


At the vicinity of an atom, a photon with energy greater than 1.02 MeV creates a positron-electron pair, and such a process is called **pair production**. Pair production also occurs in the field of an atomic electron, especially for photons with energy of more than 2.04 MeV. Pair production is not exactly the reverse of annihilation, because the former involves only one phobton, and two photons are emitted in annihilation. Note that the two electrons produced, e- and e+, are not scattered orbital electrons, but are created, *de novo*, in the energy/mass conversion of the disappearing photon.

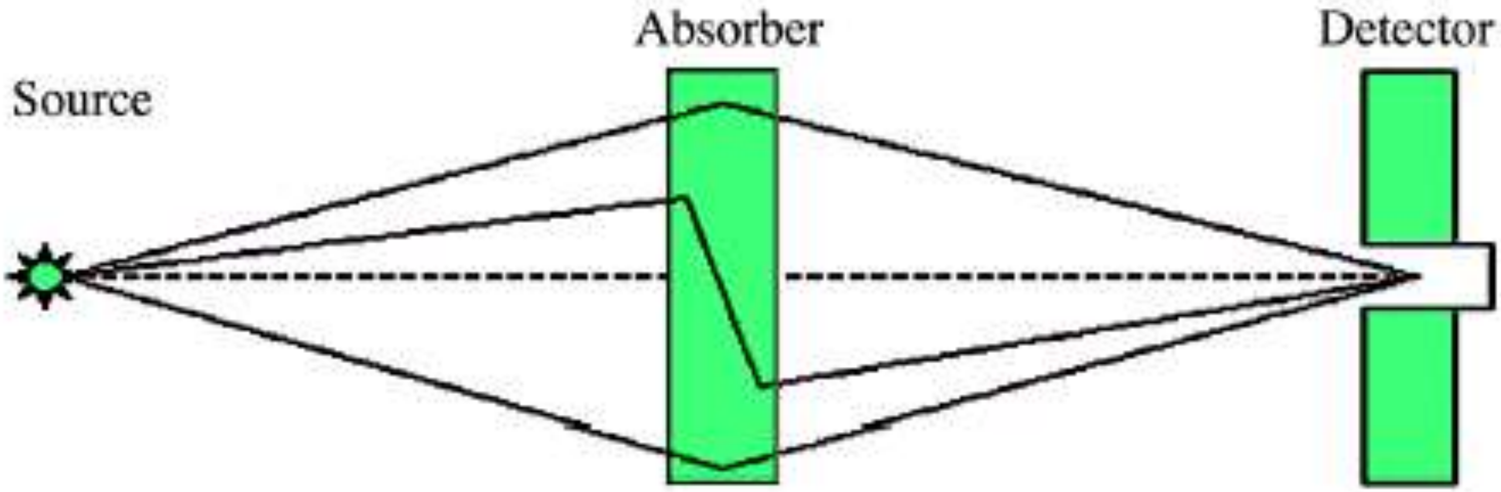
Positron annihilation:

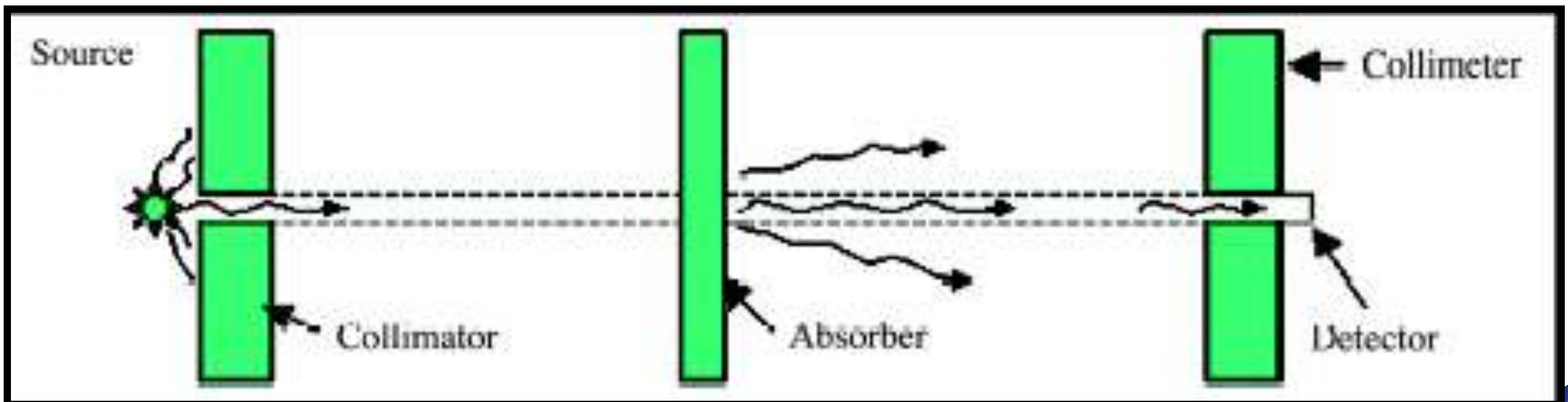
$$e^+ + e^- \rightarrow 2\,\gamma \text{ (511 keV)}$$

Relative importance of specific interactions



Attenuation & absorption of gamma radiation





Absorption of the γ-dose

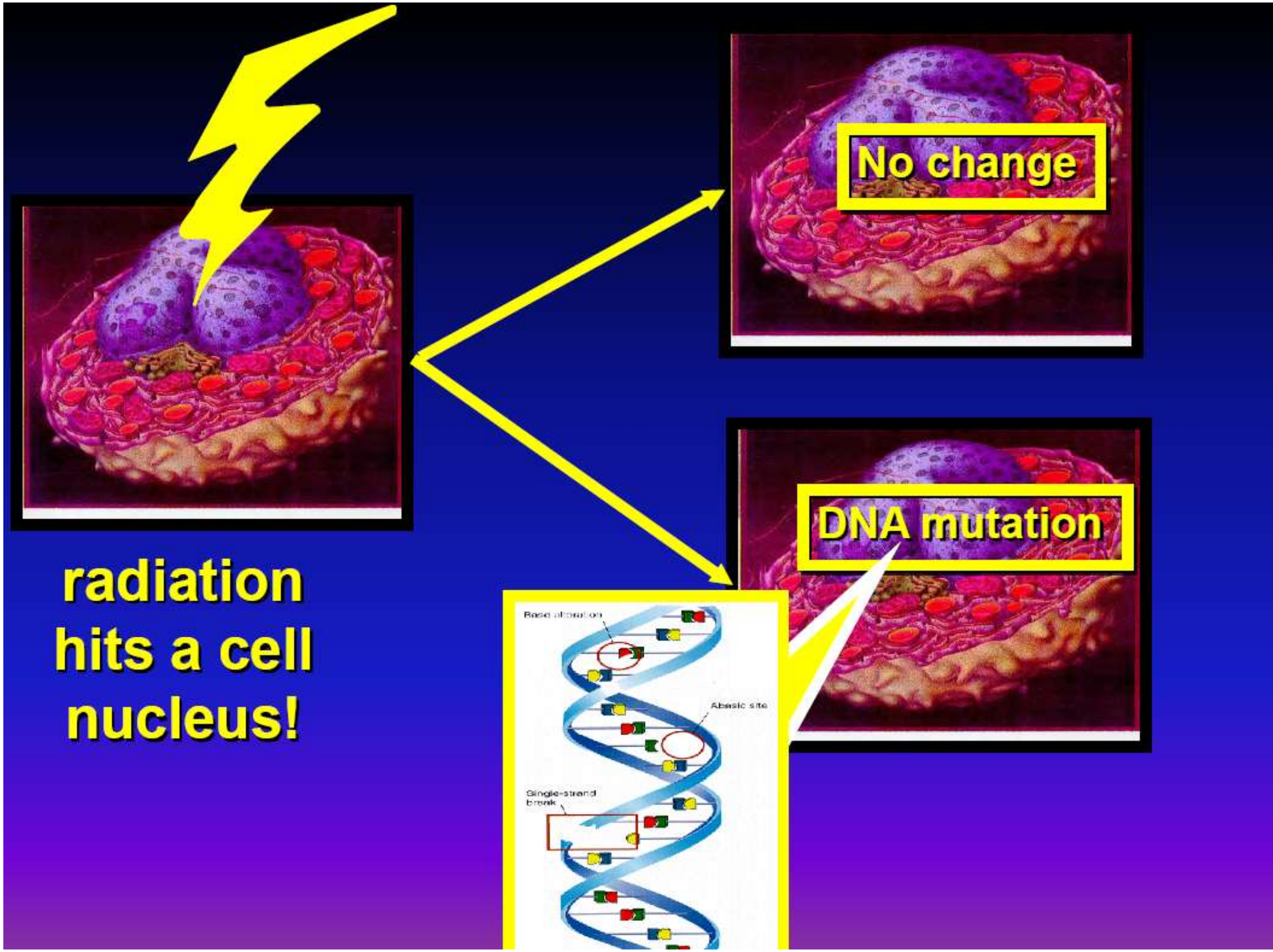
$$\mu = \mu_{pe} + \mu_{cs} + \mu_{pp}$$

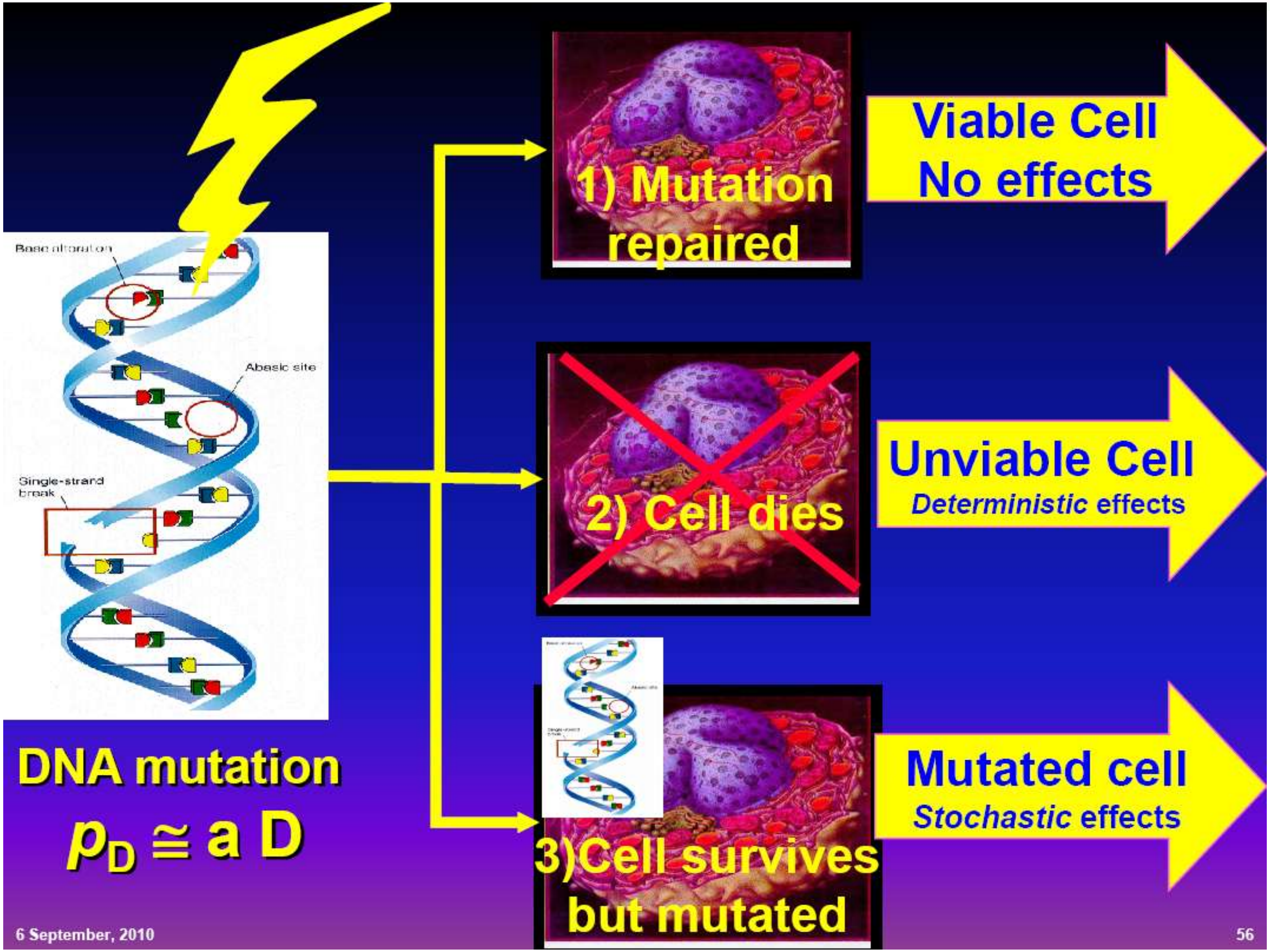
Half-value thickness

$$d_{1/2} = \ln 2 / \mu$$

Medium	0.1 MeV	0.5 MeV	1 MeV	2 MeV	5 MeV
Air	35 m	62 m	76 m	120 m	200 m
Water	4 cm	7 cm	10 cm	14 cm	23 cm
Concrete	2 cm	3 cm	5 cm	7 cm	10 cm
Iron	0.2 cm	1 cm	1 cm	2 cm	3 cm
Lead	0.01 cm	0.4 cm	0.9 cm	1.3 cm	1.4 cm

Biological effects


radiation hits a cell nucleus!
No change
DNA mutation
Base alteration
Abasic site
Single-strand break


Base alteration
Abasic site
Single-strand break
DNA mutation
$p_D \cong a\,D$
1) Mutation repaired
Viable Cell
No effects
2) Cell dies
Unviable Cell
Deterministic effects
3)Cell survives but mutated
Mutated cell
Stochastic effects

Biological Effects of Radiation

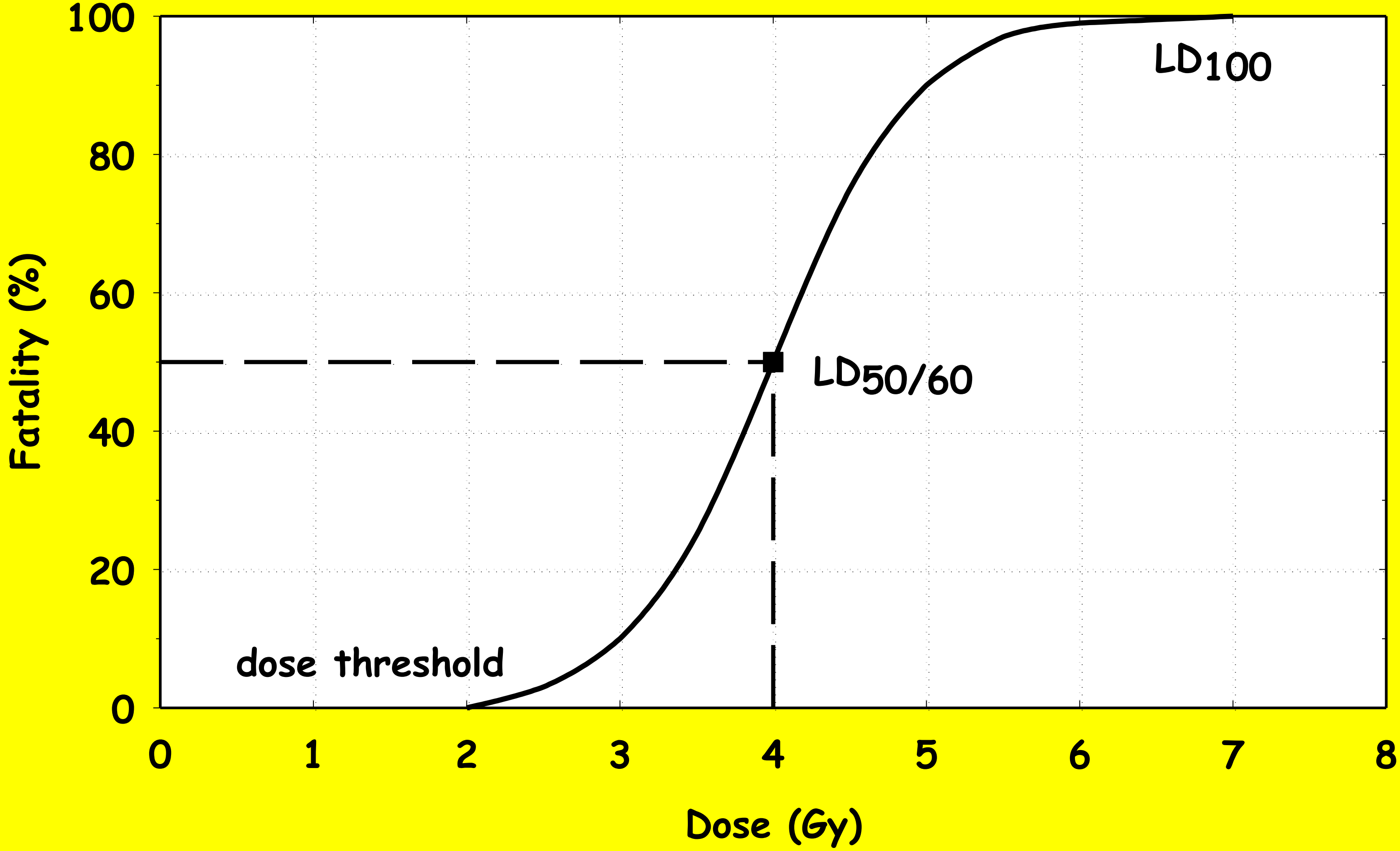
- Deterministic effects (dose threshold!)
  - acute: can be lethal!

- Stochastic effects
  - late: cancer, leukemia
  - hereditary (in offspring)
  - antenatal

Deterministic effects

- Acute radiation syndrome ARS
  - hemopoietic s. (2 – 10 Gy)
  - gastrointestinal s. (10 – 50 Gy)
  - central nervous system s. (>50 Gy)
- skin damage
- cataract
- Sterility (temporal or permanent)

DETERMINISTIC EFFECTS OF RADIATION
ARS - Acute Radiation Syndrome

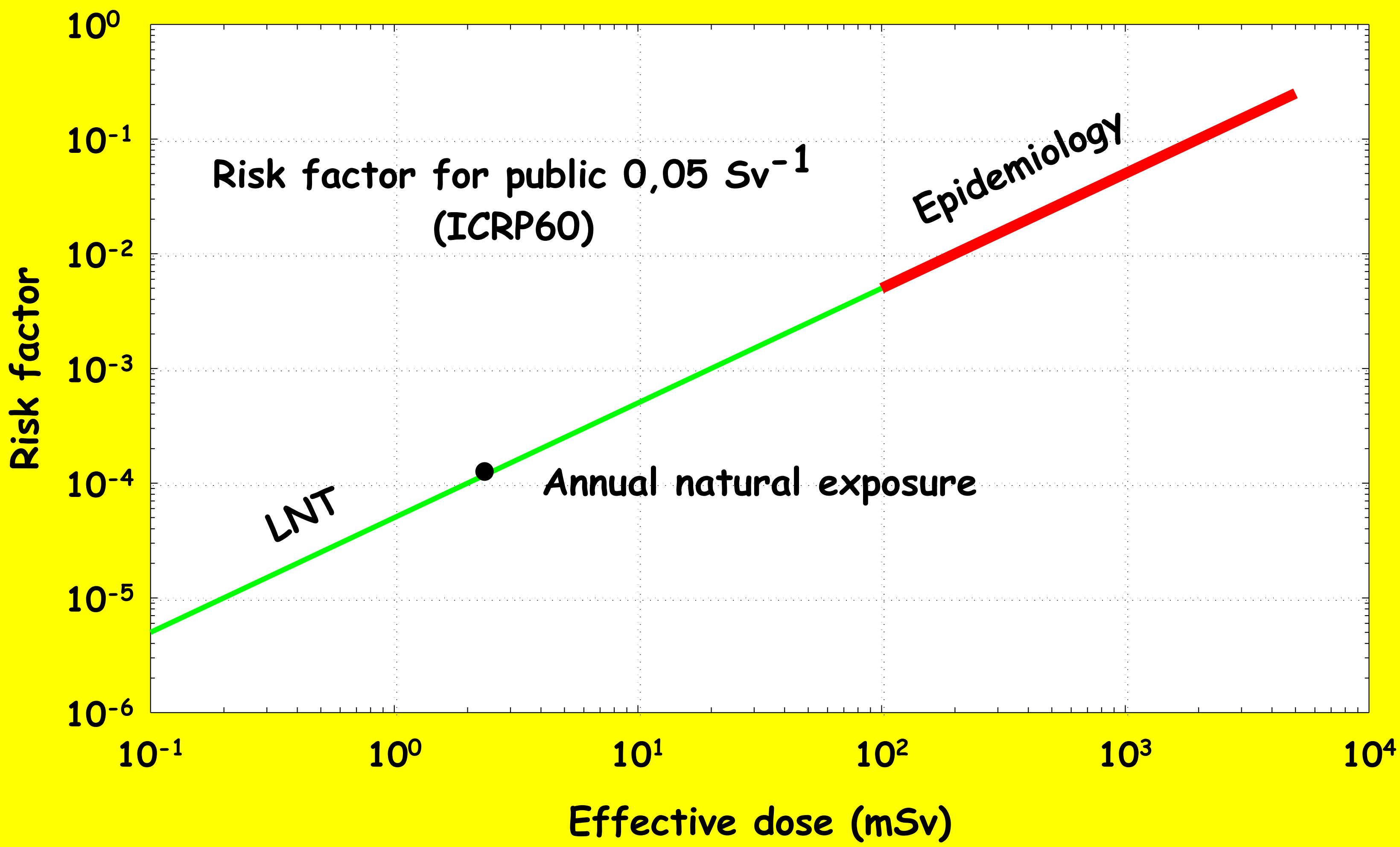


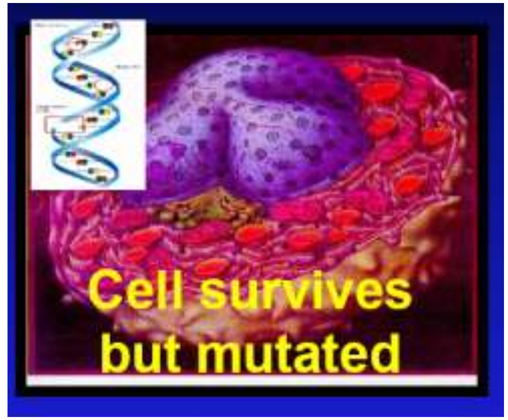
Dose	Effects on individuals	Consequences for an exposed population
Very low dose: about 10 mSv or less	No acute effects; extremely small additional cancer risk	No observable increase in the incidence of cancer, even in a large exposed group
Low dose: towards 100 mSv	No acute effects; subsequent additional cancer risk of less than 1%	Possible observable increase in the incidence of cancer, if the exposed group is very large (e.g., >100,000 people)
Moderate dose: towards 1000 mSv (acute whole body dose)	Nausea, vomiting possible, mild bone marrow depression; subsequent additional cancer risk of about 10%	Probable observable increase in the incidence of cancer, if the exposed group is more than a few hundred people
High dose: above 1000 mSv (acute whole body dose)	Certain nausea, likely bone marrow syndrome; high risk of death from about 4000 mSv (without medical treatment). Significant additional cancer risk!	Observable increase in the incidence of cancer

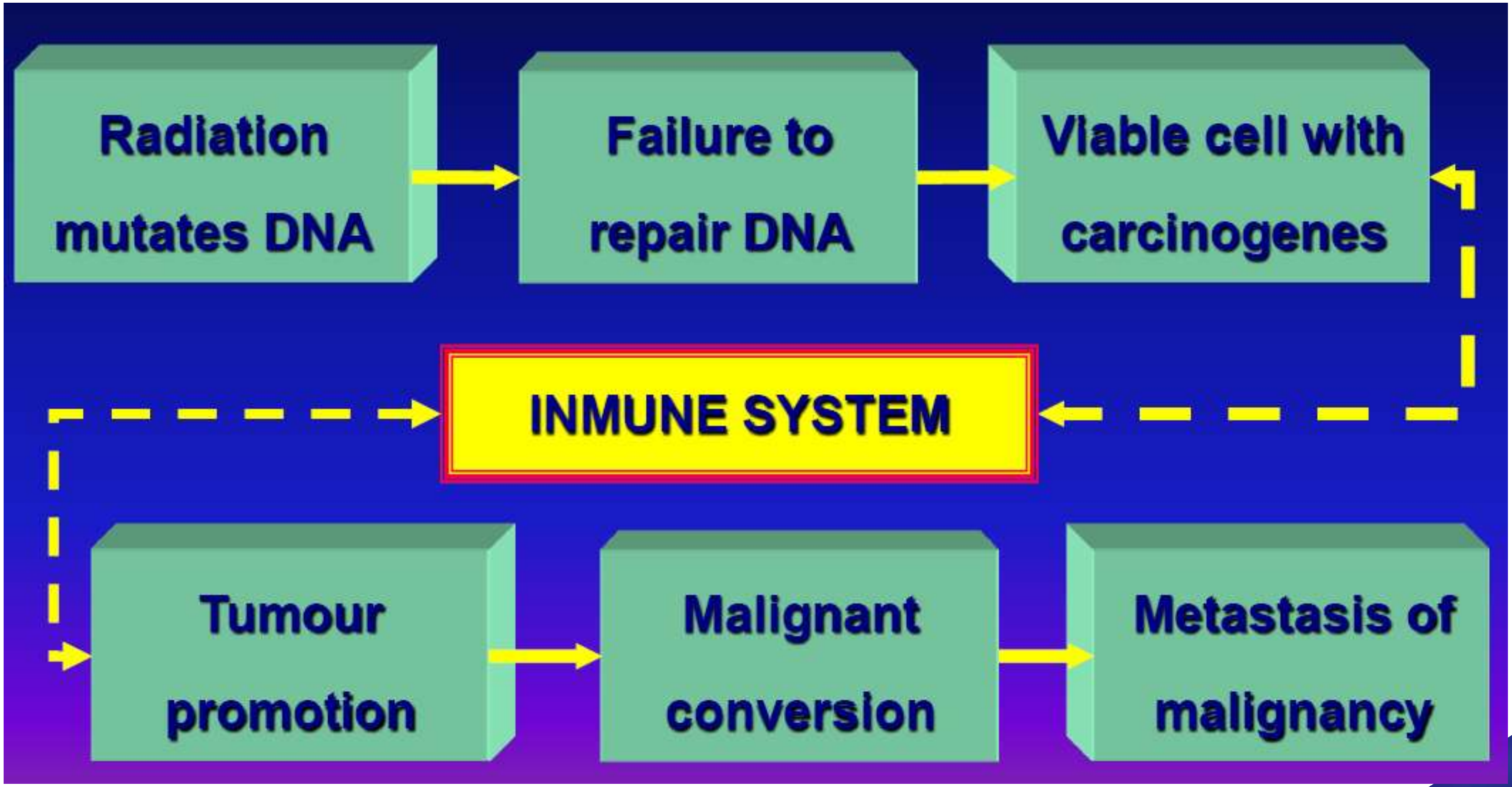
Mihran Kassabian (1870-1910)

- X-ray exposure in 1900
- death from cancer in 1910

Stochastic effects of radiation




Cell survives
but mutated


Radiation mutates DNA
Failure to repair DNA
Viable cell with carcinogenes
INMUNE SYSTEM
Tumour promotion
Malignant conversion
Metastasis of malignancy

Main features of stochastic effects

- cancer, leukemia, hereditary effects in offspring
- latent period (years, tens of years)
- probability increases with dose (LNT)

Dose and definition

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Absorbed dose and dose rate

- ✓ Interaction of radiation with matter involves transfer of energy from the radiation to the matter (biological effect % to absorbed energy)
- ✓ Radiation depends on energy and intensity
- ✓ SI unit: 1 Gy =1 J kg^{-1}
- ✓ Dose rate: rate at which the absorbed dose is received (Gy s^{-1})

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Weighting factor

- The biological effect depends on the type of radiation and the energy range

Type of radiation, R	Energy range	Quality or Weighting factor, w_R
Photons, electrons	All energies	1
Neutrons	< 10 keV	5
	10-100 keV	10
	100 keV – 2 MeV	20
	2-20 MeV	10
	>20 MeV	5
Protons	< 20 MeV	5
Alpha particles, fission fragments, heavy nuclei		20

* ICRP Publication 74, Annal of the ICRP 26 (3/4), 1996

Tissue/organs sensibility

Tissue / organ sensitivity

(stochastic effects)

Effective dose *E* $E = \Sigma\, w_T H_T$

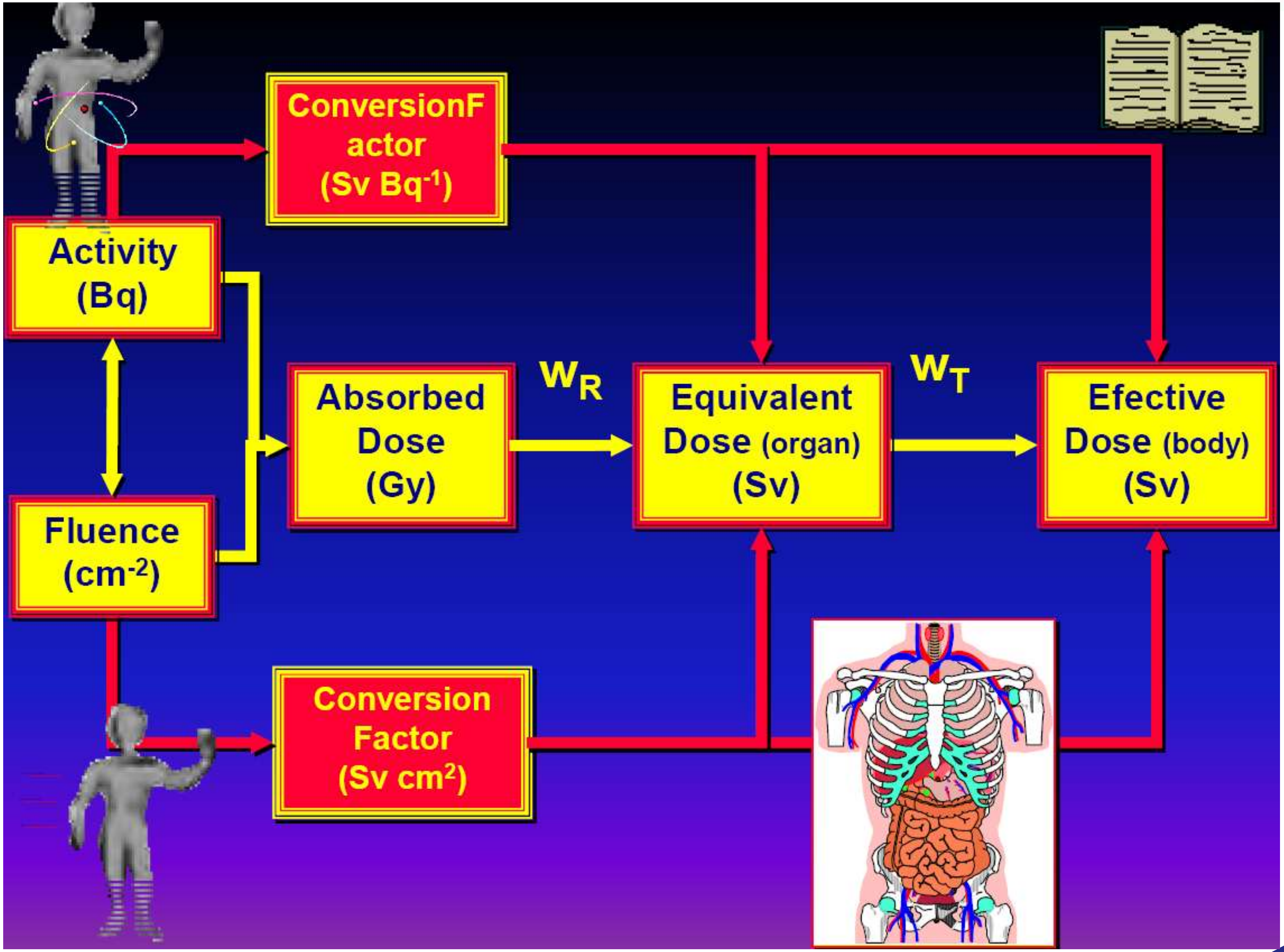
Tissue weighting factors w_T

Tissue / organ	w_T
gonads	0,20
red bone marrow, colon, lung, stomach	0,12
bladder, breast, liver, oesophagus, thyroid	0,05
skin, bone surface	0,01
remainder	0,05

Equivalent and effective dose

- Equivalent dose in a tissue or organ: $H_T = D_{T,R} \cdot \omega_R$
- If several types of radiation: $H_T = \sum_R \left(D_{T,R} \cdot \omega_R \right)$
- SI unit: 1 Sv = 1 J kg^{-1}
- Equivalent dose rate: $\frac{dH_T}{dt} = \frac{dD_{T,R}}{dt} \cdot \omega_R \quad (\text{Sv/s or mSv/h})$
- Effective dose (E) : introduce tissue weighting factor (e.g. Gonads =0.20, Skin = 0.01), hence

$$E = \sum_T \left(H_T \cdot \omega_T \right)$$


ConversionFactor (Sv Bq-1)
Activity (Bq)
Absorbed Dose (Gy)
WR
Equivalent Dose (organ) (Sv)
WT
Efective Dose (body) (Sv)
Fluence (cm-2)
Conversion Factor (Sv cm2)

The radiation doses in short words

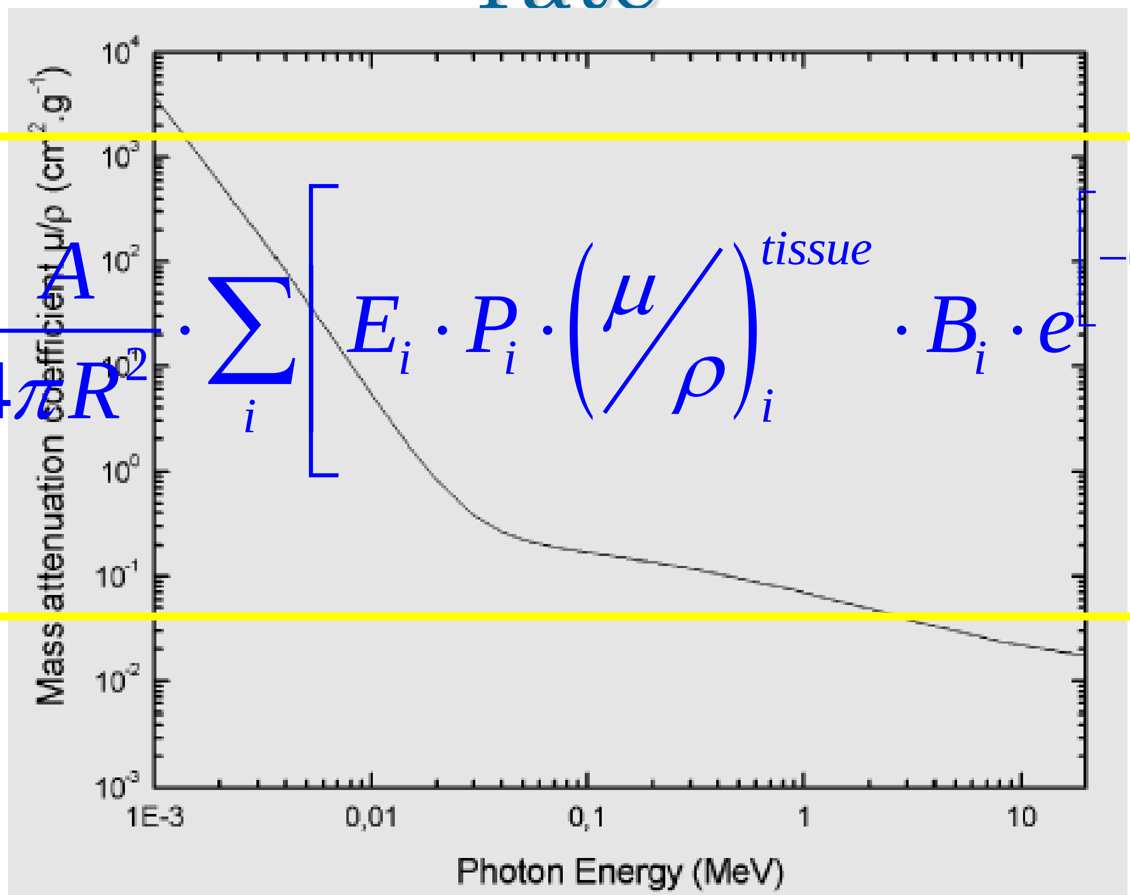
- Absorbed dose: amount of radiation aborbed per unit mass of material (Gy = $J.kg^{-1}$)
- Dose rate: absorbed dose per unit time ($Gy.s^{-1}$)
- Equivalent dose: dose rate weighted for the biological effects of different types of radiation ($Sv.h^{-1}$)
- Effective rate: equivalent dose weighted to take into account the damage sensitivities to different tissues ($Sv.h^{-1}$)

How much is a mSv?

- 1 radiography = 1 mSv
- 1 year of natural radiation = 1 – 10 mSv

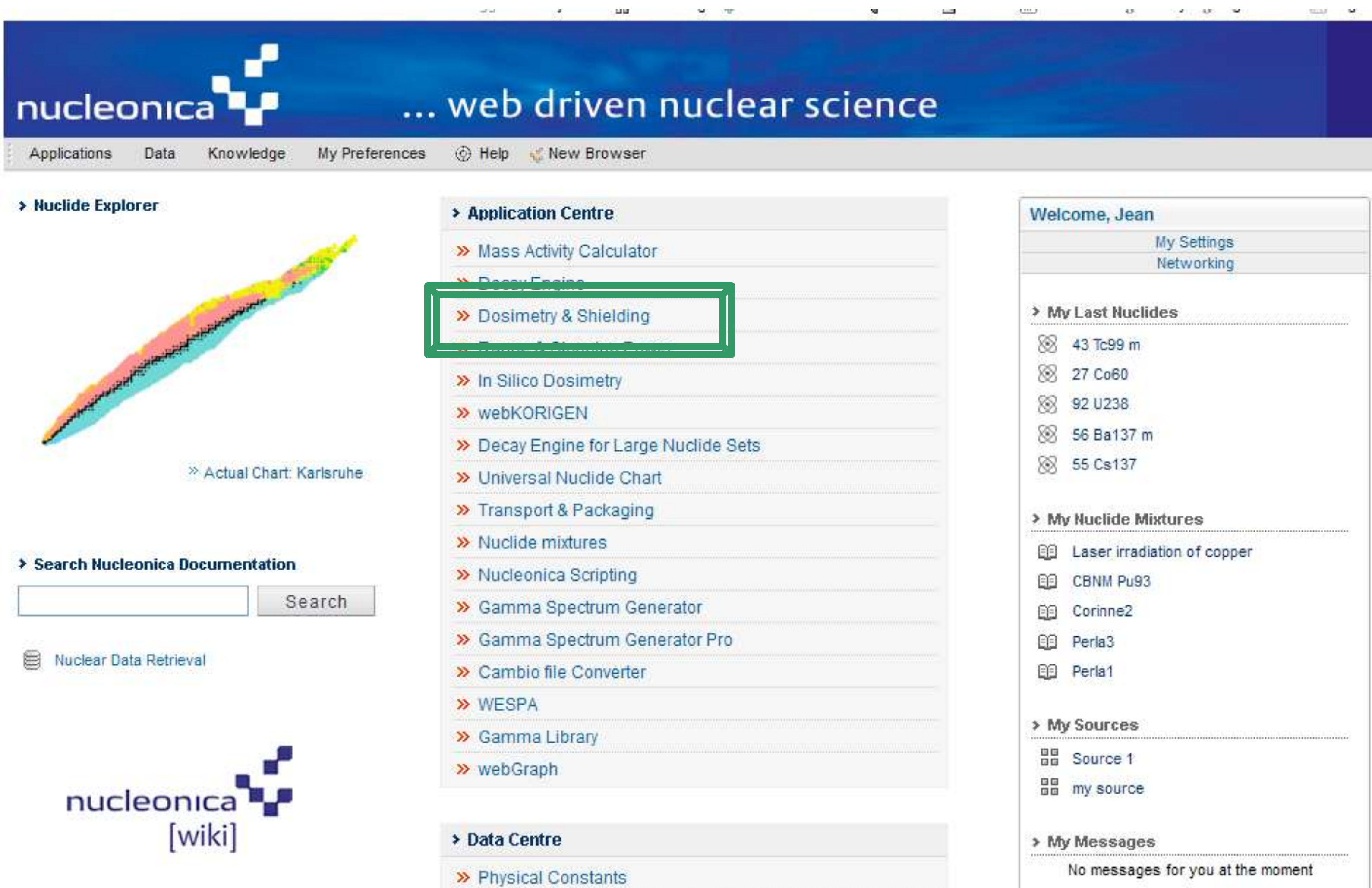
- Dose from sleeping next to a human for 8 hours every night: 0.02 mSv/yr
- Dose from smoking 30 cigarettes a day: 13-60 mSv/year
- In most countries: maximum permissible dose to radiation workers is 20 mSv/year
- Dose limit applied to workers during Fukushima emergency: 250 mSv/year

Absorption in tissue and calculation of the equivalent dose rate



$$\frac{dH}{dt} = \frac{A}{4\pi R^2} \cdot \sum_i \left[E_i \cdot P_i \cdot \left(\mu / \rho \right)_i^{tissue} \cdot B_i \cdot e^{\left[-\left(\mu / \rho \right)_i^{shield} \rho d \right]} \right]$$

Dosimetry in Nucleonica



Exercice 1: Irradiator

Irradiators are γ-sources (e.g. ^{137}Cs, ^{60}Co) used for food irradiation, radiation induced mutation, sterilization, medicine purposes, etc…

Exercise: A ^{60}Co gamma ray irradiation containing a 2TBq source is directed at a 30 cm thick concrete wall. The wall is situated at 7.5 m from the source. What the exposure rate behind the wall?

Co60
10.47 m | 5.27 y

Dosimetry and Shielding

27 Cobalt

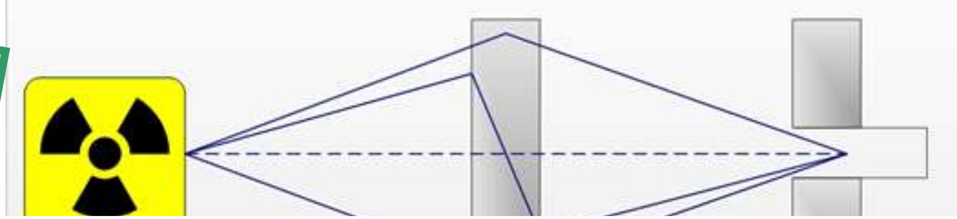
Questions, remarks, suggestions can be posted in the **forum**

Current Chart: Karlsruhe

Element: Co | Mass: 60 | Nuclide Mixtures Selector

Dosimetry and Shielding | Dose rate/Thickness graph | Options

Source strength		Shielding material		Dose rate (μSv/h)
Activity(Bq)	2e12	Concrete	30 cm	???



Half-Value Shield Thickness(cm)	1.31E+01
Tenth-Value Shield Thickness(cm)	3.05E+01
Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h)	2.37E-01
Gamma Dose Rate (μSv/h)	**1.17E+03**
Effective Build-up factor	6.61E+00
Effective Number of Mean Free Paths (μ·d)	4.17E+00

Exercise 1 (2)

- Regulation impose an exposure rate outside the room of 7.5 µSv/h max. What thickness of wall would we then need?
- We want to restrict the exposure rate inside the room (@1m from the irradiator) to 10 µSv/h using lead. Calculate the required thickness.

Co60
10.47 m | 5.27 y

Dosimetry and Shielding

27 Cobalt

Current Chart: Karlsruhe

Questions, remarks, suggestions can be posted in the **forum**

Dosimetry and Shielding | Dose rate/Thickness graph | Options

Dosimetry and Shielding Settings

Energy range option:

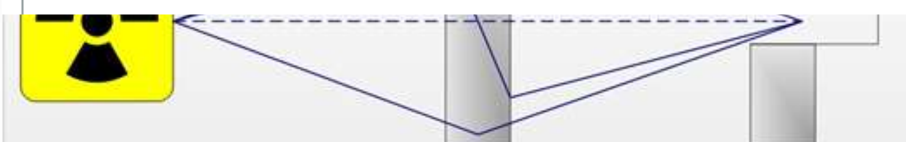
- ( ) Only Gamma
- ( ) Only X-rays
- (•) Gamma and X-rays
- [x] Threshold set

Mode of operation option:

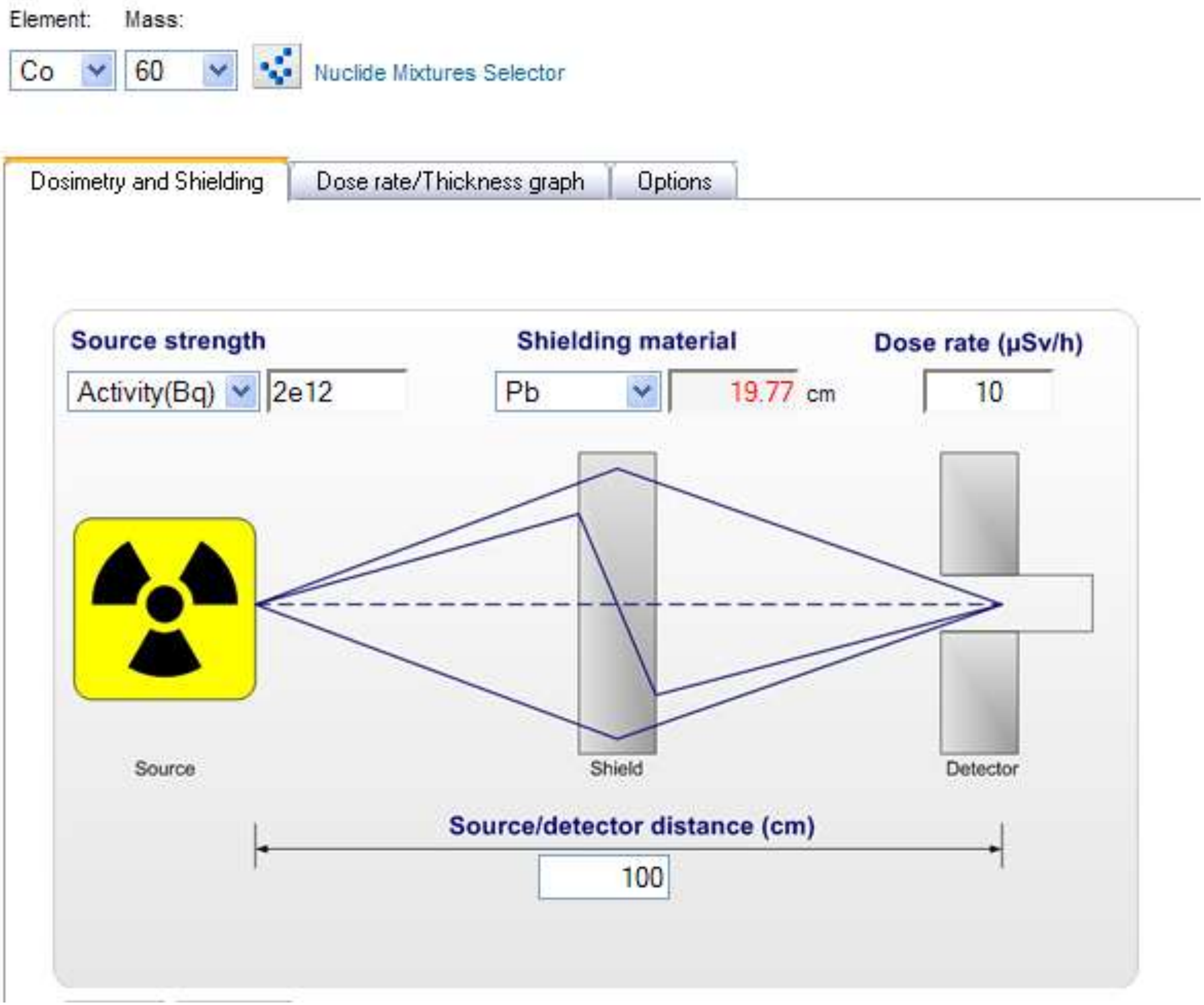
- ( ) Gamma Dose Rate
- (•) Shield Thickness
- ( ) Source Strength

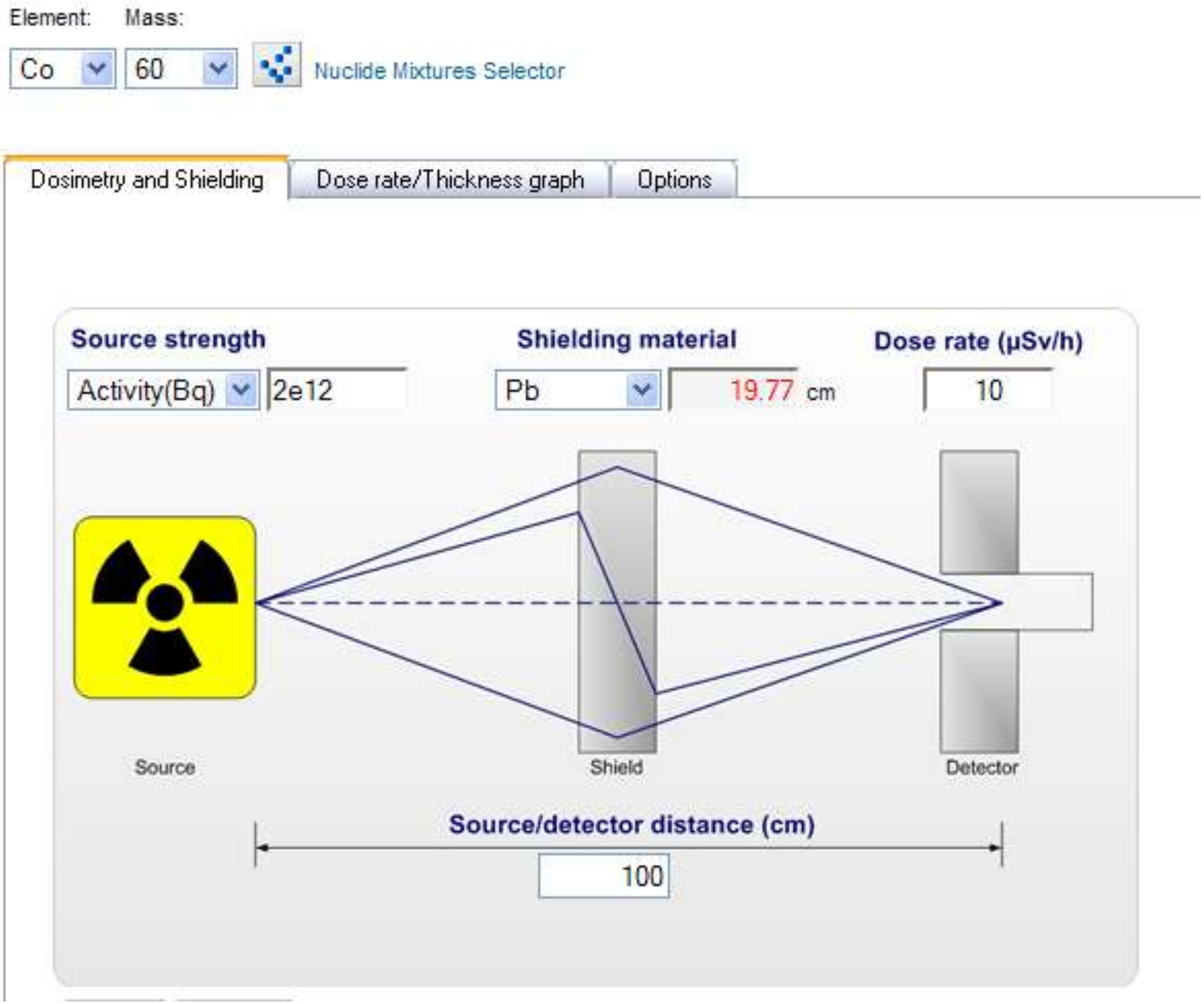
Threshold energy (keV): 15

Result Detail option: [ ] Show Nuclides



Half-Value Shield Thickness(cm)	1.31E+01
Tenth-Value Shield Thickness(cm)	3.05E+01
Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h)	3.37E-01
Shielding Thickness required(cm)	**74.57**
Resulting Gamma Dose Rate(μSv/h)	7.50E+00
Effective Build-up factor	2.07E+01
Effective Number of Mean Free Paths (μ·d)	1.03E+01


Element:
Mass:
Co
60
Nuclide Mixtures Selector
Dosimetry and Shielding
Dose rate/Thickness graph
Options
Source strength
Activity(Bq)
2e12
Shielding material
Pb
19.77
cm
Dose rate (μSv/h)
10
Source
Shield
Detector
Source/detector distance (cm)
100


Element:
Mass:
Co
60
Nuclide Mixtures Selector
Dosimetry and Shielding
Dose rate/Thickness graph
Options
Source strength
Activity(Bq)
2e12
Shielding material
Pb
19.77 cm
Dose rate (µSv/h)
10
Source
Shield
Detector
Source/detector distance (cm)
100

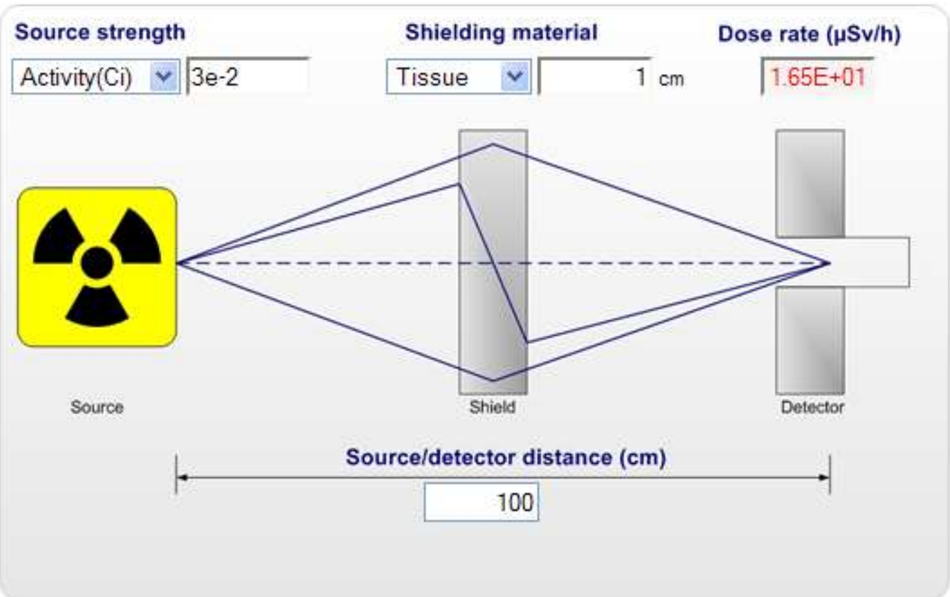
Exercise 2: ^{99m}Tc in medicine

^{99m}Tc is used in radioactive isotope medical tests, for example as a radioactive tracer that medical equipment can detect in the body. It is well suited to the role because it emits readily detectable 140 keV gamma rays, and it has a short half-life of 6.01 hours (meaning it has almost completely decayed to ^{99}Tc in 24 hours). A patient is injected 30 mCi of ^{99m}Tc. He is considered as an unshielded source during the time there is radioactivity in his body. Thus the staff is exposed to radiation. What is the equivalent dose rate that a staff member can be exposed to? (medium is tissue, 1 cm thick @1 m distance)

Element: Mass:

Tc | 99 m | Nuclide Mixtures Selector

Dosimetry and Shielding | Dose rate/Thickness graph | Options



Start | Reset

Half-Value Shield Thickness(cm)	2.89E+00
Tenth-Value Shield Thickness(cm)	1.27E+01
Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h)	2.00E-02
Gamma Dose Rate (µSv/h)	**1.65E+01**
Effective Build-up factor	1.00E+00
Effective Number of Mean Free Paths (µ·d)	3.00E-01

Distance From Patient (cm)	Exposure Rate (mR/h per mCi)	Exposure for Typical Procedures (mR)†	
		Thallium (3.5 mCi)	^{99m}Tc (30 mCi)
1	698	1,629	13,960
5	28	65	558
15	3	7	60
30	0.8	1.8	16
100	0.07	0.2	1.4

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